

# **U.S. PATENT APPLICATION**

**TITLE:** HIGH ELECTRON MOBILITY DEVICES

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## HIGH ELECTRON MOBILITY DEVICES

### 1. Field of the Invention

The present invention relates to high electron mobility transistors (HEMTs), also called hetero-structure field-effect transistors (HFETs), having polarization-induced charge of high density.

### 2. Description of the Related Art

High electron mobility transistors (HEMT) are field effect devices that use high mobility carriers. Most conventional semiconductor devices use semiconductor layers doped with n-type impurities to generate electrons (or p-type impurities to generate holes) as carriers. However, the impurities cause the electrons (or holes) to slow down because they alter periodicity of the lattice structure, i.e., they form defects that cause collisions. On the other hand, HEMTs provide for carriers with higher mean free paths and thus higher frequency of operation.

Fig. 1 shows diagrammatically a GaAs HEMT 2, as known in the prior art. HEMT 2 includes a source electrode 6, a gate electrode 8, and a drain electrode 10. HEMT 2 also includes an un-doped GaAs layer 14 acting as a channel layer on a semi-insulating GaAs substrate 12. On un-doped GaAs layer 14, there is an un-doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer 16 and a doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer 18, which is an electron-supplying layer.

The hetero-interface of HEMT 2 is made of two materials: a wide band gap barrier layer (i.e., the  $\text{AlGaAs}$  layer) and a channel layer (i.e., the GaAs layer). Due to conduction band discontinuity  $\Delta E_C$  and electric field at the interface, there is electron gas 15 formed in the un-doped GaAs layer 14 along the interface to  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer 16.

HEMT 2 includes electron gas layer (or volume) 15 formed in the un-doped GaAs layer 14 along the interface to  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer 16. Specifically, electrons generated in n-type  $\text{AlGaAs}$  layer 18 drop completely into GaAs layer 14. In GaAs layer 14, which has a substantially "perfect" structure without doped impurities, these electrons have a high mobility, and can move undergoing much less collisions. Typically, the maximum available electron density for single modulation-doped quantum wells is about  $4 \times 10^{12} \text{ cm}^{-2}$ .

The un-doped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer 20 increases the breakdown voltage of HEMT 2. The Al-content  $x$  of the layer 16 or 18, represented by the composition  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ , is desired to have a relatively large value to increase the sheet density of the two-dimensional electron gas 15 located in GaAs channel layer 14. Layers 16 and 18 are generally in the range of about  $x = 0.2$  to about 0.3.

Fig. 1A shows diagrammatically a band gap diagram of HEMT 2 under thermal equilibrium. At the GaAs/AlGaAs interface, the conduction band  $E_c$  is located below the Fermi level  $E_F$ , enabling formation of a two dimensional electron gas (2DEG). This two-dimensional electron gas has a Gaussian electron density distribution. Under a biased state this electron density distribution spreads out. Under the condition of thermal equilibrium, the electron-supplying layer 18 is entirely depleted. When a positive bias voltage is applied to gate electrode 8, an electrically neutral region appears in layer 18 and grows with an increase of the biased voltage. Thus, the electron density of the  $n^+$ -type  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer 18 increases with the gate voltage. The mobility of the electrons in the electron-supplying layer 18 ( $n^+$ -type  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ) is lower than that in GaAs channel layer 14 as explained above. On the other hand, negative bias applied to the gate depletes the electron gas 15 until no current will flow.

Fig. 2 shows diagrammatically another type of a HEMT having a doped barrier layer. HEMT 25 was described in IEEE Transaction on Electron Devices, Vol. 48 (2001), pages 581-585. A HEMT 25 includes a quantum well structure made of AlN, GaN and AlGaN epitaxial layers 31, 32, 33, 34 and 35. Deposited on a highly resistive 4H-SiC substrate 30, there are AlN buffer layer 31, a 2  $\mu\text{m}$  GaN layer 32, a 2 nm un-doped  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$  spacer 33, a doped  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$  layer 34 being 15 nm thick and having a doping level  $1 \times 10^{19} \text{ cm}^{-3}$ , and a 10 nm un-doped AlGaN cap layer 35. Hall measurements on HEMT 25 revealed the concentration of  $1.1 \times 10^{13} \text{ cm}^{-2}$  of the 2D electron gas and an electron mobility of  $1100 \text{ cm}^2/\text{Vs}$ . HEMT 25 with a 0.12  $\mu\text{m}$  gate-length had a DC characteristics with the maximum drain current of 1.19 A/mm and the transconductance of 217 mS/mm.

Referring to FIG. 3, another type of a gallium nitride HEMT was described in the Proceeding of the Third International EuroConference on Advanced Semiconductor Devices, Smolenice Castle, Slovakia, October 2000, edited by J. Osvald, Š. Haščík, J. Kuzmík, J. Breza, IEEE Catalog No. 00EX386, pages 47-54.

Fig. 3 shows diagrammatically HEMT 40, which includes a substrate, an AlN layer 41, a GaN layer 42, a AlGa<sub>N</sub> layer 43, and contacts 45 and 47. In HEMT 40, the electron carriers are accumulated in the QW channel due to the polarization fields only, as shown in Fig. 3A. The heterostructure of HEMT 40 was formed by 20 nm nucleation layer 41 followed by a 2-3  $\mu\text{m}$  thick un-doped GaN layer 42, and about 20 nm un-doped AlGa<sub>N</sub> layer 43, which included about 15-20 % of AlN. In this quantum well (QW) structure, Hall effect measurements at room temperature typically yielded the 2DEG sheet concentration of  $5 \times 10^{12} \text{ cm}^{-2}$  and the Hall mobility of  $1200 \text{ cm}^2/\text{Vs}$ . HEMT 40 with a  $0.7 \mu\text{m}$  gate-length had the peak current of  $210 \text{ mA/mm}$  and the maximum transconductance of  $110 \text{ mS/mm}$ .

Referring to Fig. 3A, HEMT 40 utilizes a piezoelectric effect present in the AlGa<sub>N</sub>/GaN QW structure. Un-doped AlGa<sub>N</sub> barrier layer 43 is tensile strained on top of GaN channel layer 42 exhibiting piezoelectric field  $P_{\text{piezo}}$  of identical orientation with differential spontaneous polarization  $\Delta P_0$ . A high density 2DEG accumulates in channel 42 QW due to superposition of the piezoelectric and differential spontaneous polarization fields, shown in FIG. 3A. High power performance requires high 2DEG density in the QW, and high  $\Delta E_c$  is important to keep the free carriers electron confined. Theoretically, the  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$  QW exhibits  $\Delta P_0 = -1.04 \times 10^{-6} \text{ Ccm}^{-2}$ ,  $P_{\text{piezo}} = -6.9 \times 10^{-7} \text{ Ccm}^{-2}$  giving the total electron charge density  $n_{\text{total}} = 1.08 \times 10^{13} \text{ cm}^{-2}$ . Corresponding 2DEG density is substantially higher than we can expect for any other III-V device where polarization phenomena does not dominate. However, surface depletion effect and/or layers imperfections may lead to lower Hall measurement electron charge density data as indicated above for our case. In HEMT 40, no extra doping is necessary to get polarization-induced charge.

There have been suggestions to add small amounts of In to AlGa<sub>N</sub> for the purpose of eliminating strain with respect to GaN and perhaps improved lattice matching of InAlGa<sub>N</sub> to the lattice of GaN. This may change the maximal electron charge density to about  $1.4 \times 10^{13} \text{ cm}^{-2}$ , which is not a much of a change when compared to prior art structures described herein.

There is a need for HEMTs with even higher electron charge density to obtain even better device performance.

### Summary of the Invention

The present invention relates to high electron mobility transistors (HEMTs), also called hetero-structure field-effect transistors (HFETs) having polarization-induced charge of high density. The present invention also relates to a method of fabricating such HEMTs (or HFETs). The present invention also relates to high frequency, high power or low noise devices such as low noise amplifiers, amplifiers operating at frequencies in the range of 1 GHz up to 400 GHz, radars, portable phones, satellite broadcasting or communication systems, or other systems using the described HEMTs.

According to one aspect, a HEMT (or HFET) includes a substrate; and a quantum well layered structure including at least a barrier layer and a channel providing the total 2DEG density of above about  $n_{\text{total}} = 1.1 \times 10^{13} \text{ cm}^{-2}$ .

According to another aspect, a HEMT (or HFET) includes a substrate; and a layered quantum well structure, made of III-nitrides, including at least a barrier layer and a channel layer wherein barrier layer contains  $\text{In}_x\text{Al}_{1-x}\text{N}$ , where  $x$  is in the range of about  $0 \leq x \leq 0.30$ .

According to yet another aspect, a III-nitrides HEMT (or HFET) includes a substrate and a cation-polarity layered structure including at least a barrier layer and a channel layer. Due to high polarization fields in the III-nitrides QW structure, a high-density electron charge is accumulated at the barrier/channel layer QW hetero-interface. The current transport is facilitated through the QW 2DEG. Preferably, the QW 2DEG density is increased by the use of a barrier layer containing  $\text{In}_x\text{Al}_{1-x}\text{N}$  (wherein  $x$  is in the range of about  $0 \leq x \leq 0.30$ ) lattice matched or strained to the bottom layer.

Preferably, the channel layer includes GaN and the barrier layer includes lattice matched  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$ . Alternatively, the barrier layer includes  $\text{In}_x\text{Al}_{1-x}\text{N}$ , wherein  $x$  is in the range of about  $0 \leq x < 0.17$ .

According to another embodiment, a III-nitrides HEMT (or HFET) includes a barrier layer having  $\text{In}_x\text{Al}_{1-x}\text{N}$ , wherein  $x$  is in the range of about  $0.17 < x \leq 0.25$ , and a channel layer having GaN. The quantum well structure includes several unique properties that made the III-nitrides HEMT suitable for high power, high frequency and high temperature applications.

According to yet another embodiment, a III-nitrides HEMT (or HFET) includes a barrier layer having  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$ , and a channel layer having  $\text{In}_y\text{Ga}_{1-y}\text{N}$ , wherein  $y$  is in the range of about  $0 < y \leq 1$ . Alternatively, the barrier layer includes  $\text{In}_x\text{Al}_{1-x}\text{N}$ , wherein  $x$  is in the range of about  $0 \leq x < 0.17$  and the channel layer includes  $\text{In}_y\text{Ga}_{1-y}\text{N}$ , wherein  $y$  is in the range of about  $0 < y \leq 1$ . Alternatively, the barrier layer includes  $\text{In}_x\text{Al}_{1-x}\text{N}$ , wherein  $x$  is in the range of about  $0.17 < x \leq 0.30$ , and the channel layer includes  $\text{In}_y\text{Ga}_{1-y}\text{N}$ , wherein  $y$  is in the range of about  $0 < y \leq 1$ .

These HEMTs use a  $\text{InAlN}$  barrier layer (which replaces a  $\text{AlGaIn}$  layer) thus forming a  $\text{InAlN}/(\text{In})\text{GaN}$  QW structure (instead of a prior art  $\text{AlGaIn}/\text{GaIn}$  QW structure) even though this approach is counter-intuitive and at this time  $\text{InAlN}$  is more difficult to grow on  $\text{GaIn}$  than  $\text{AlGaIn}$ .

According to yet another aspect, a HEMT (or HFETs) includes a substrate; and a quantum well layered structure including at least a barrier layer and a channel providing the total 2DEG density of above about  $n_{\text{total}} = 1.1 \times 10^{13} \text{ cm}^{-2}$ .

According to yet another aspect, a HEMT (or HFETs) includes a substrate; and a quantum well layered structure including at least a barrier layer and a channel providing a 2DEG of high density due the polarization phenomena and impurity doping of a layer included in the quantum well structure.

Preferably, in the above devices, high drain currents, power capabilities or low noise properties result from a high QW polarization-induced 2DEG alone or in combination with a doped layer providing charge carriers.

### Brief Description of the Drawings

FIG. 1 illustrates an  $\text{AlGaAs}/\text{GaAs}$  HEMT according to prior art.

FIG. 1A is a band gap diagram of the HEMT shown in FIG. 1.

FIG. 2 illustrates an  $\text{AlGaIn}/\text{GaIn}$  HEMT with a doped barrier according to prior art.

FIG. 3 illustrates an  $\text{AlGaIn}/\text{GaIn}$  HEMT with an un-doped barrier layer according to prior art.

FIG. 3A is a band gap diagram of the HEMT shown in FIG. 3 exhibiting polarization.

FIG. 4 is a cross-sectional view of an  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaIn}$  HEMT according to a first preferred embodiment.

FIG. 4A is a band gap diagram of an  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$  quantum well used in the HEMT shown in FIG. 4.

FIG. 4B is a band gap diagram of an  $\text{In}_{0.25}\text{Al}_{0.75}\text{N}/\text{GaN}$  quantum well.

FIG. 5 is a cross-sectional view of an  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  HEMT according to a second embodiment.

FIG. 5A is a band gap diagram of an  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  quantum well used in the HEMT shown in FIG. 5.

FIG. 5B is a band gap diagram of an  $\text{In}_{0.15}\text{Al}_{0.85}\text{N}/\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$  quantum well used in an  $\text{In}_{0.15}\text{Al}_{0.85}\text{N}/\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$  HEMT.

FIG. 5C is a band gap diagram of the  $\text{In}_{0.30}\text{Al}_{0.70}\text{N}/\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$  quantum well used in an  $\text{In}_{0.3}\text{Al}_{0.7}\text{N}/\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$  HEMT.

FIG. 6 is a graph of calculated drain current and transconductance characteristics of the  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$  and  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  HEMTs, respectively, in comparison to the  $\text{AlGaIn}/\text{GaIn}$  HEMT.

FIG. 6A is a graph of calculated drain current and transconductance characteristics of the  $\text{In}_{0.25}\text{Al}_{0.75}\text{N}/\text{GaIn}$ ,  $\text{In}_{0.15}\text{Al}_{0.85}\text{N}/\text{In}_{0.10}\text{Ga}_{0.9}\text{N}$ , and  $\text{In}_{0.30}\text{Al}_{0.70}\text{N}/\text{In}_{0.10}\text{Ga}_{0.9}\text{N}$  HEMTs, respectively, in comparison to the  $\text{AlGaIn}/\text{GaIn}$  HEMT.

FIG. 7 illustrates for III-nitrides the dependence of energy gap ( $\Delta E_g$ ) on a lattice constant ( $a_0$ ) for various compounds.

Fig.8 shows calculated  $\text{In}_x\text{Al}_{1-x}\text{N}/\text{GaIn}$  QW free electron charge density, HEMT open channel drain current, threshold voltage and the barrier layer strain as a function of the In molar fraction in  $\text{InAlIn}$ .

Fig.9 shows calculated  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_y\text{Ga}_{1-y}\text{N}$  QW free electron charge density, HEMT open channel drain current, threshold voltage and the channel layer strain as a function of the In molar fraction in  $\text{InGaIn}$ .

### Description of the Preferred Embodiments

Fig. 4 illustrates a HEMT 60 according to a first preferred embodiment. HEMT 60 includes a substrate 61, a quantum well (QW) structure 62 and electrodes 72 and 74. Preferably, quantum well structure 62 includes an  $\text{AlIn}$  buffer layer 64, an un-doped  $\text{GaIn}$  layer 66, and an un-doped  $\text{InAlIn}$  layer 68. A doped  $n^+$ - $\text{GaIn}$  layer 70 is used to form ohmic contacts with source and drain electrodes 72.

HEMT 60 is a III-nitride HEMT fabricated on a (0001) 6H-SiC substrate 61 using molecular-beam epitaxy (MBE) or metal-organic vapor phase epitaxy (MOVPE). AlN buffer layer 64 has a thickness in the range of 10nm to 40 nm and preferably about 20 nm. GaN layer 66 has a thickness in the range of 1  $\mu\text{m}$  to 3  $\mu\text{m}$  and preferably about 2  $\mu\text{m}$  and the carrier concentration preferably less than about  $1 \times 10^{16} \text{ cm}^{-3}$ . An un-doped  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 68 has a thickness in the range of about 5 nm to 30 nm, and preferably about 15 nm. The highly doped  $n^+$  GaN cap layer 70 has a thickness in the range of about few nm to tens of nanometers, and preferably about 15 nm and has a carrier concentration of more than  $5 \times 10^{18} \text{ cm}^{-3}$ . HEMT 60 has a Pt/Au gate electrode 74 and Ti/Al/Ni/Au source/drain electrodes 72.

MBE or MOVPE can be used to grow QW structure 62 on 6H-SiC substrate 61 (but other substrates such as bulk GaN crystal, 4H-SiC, sapphire,  $\text{MgAl}_2\text{O}_4$ , glass and ZnO, quartz glass, GaAs, Si may also be used as long as epitaxial growth can be achieved).

Preferably, MOVPE is used to grow AlN buffer 64 at 530° C on substrate 61 (but other buffer layers such as GaN can be used providing layers cation polarity is maintained). Next, MOVPE is continued to grow GaN layer 66 at 1000° C, while supplying a flow of ammonium gas. Precursors for Al and In are added for subsequent In and/or Al containing ternary compounds, which can be grown at about 720° C. The process provides cation-polarity epitaxial layers.

After depositing QW structure 62, HEMT 60 is fabricated using photolithography for resist patterning and subsequent mesa etching, which is necessary for device isolation. The etching is done by an electron-cyclotron resonance reactive-ion etching (ECR RIE) system using  $\text{Cl}_2/\text{CH}_4/\text{H}_2/\text{Ar}$  gas mixture. Subsequent resist patterns and lift-off are used to form ohmic contacts 72 and later Schottky contact 74. Ohmic contacts 72 (Ti/Al/Ni/Au) are placed on  $n^+$  GaN cap layer 70 and alloyed at 850 °C for 2 minutes. Next,  $n^+$ -GaN cap layer 70 is RIE etched (in  $\text{CH}_4/\text{H}_2$  gas mixture) down to  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 68 through a defined resist opening. To create gate electrode 74, a Pt/Au film is vacuum evaporated. After metal has been lifted off, RIE-induced damage in the surface of  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 68 is removed applying annealing at 470° C for 40 seconds. Bonding pads made of Ti/Au are formed at the end.



Fig. 4A illustrates a band gap diagram of the  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$  QW structure 62. In QW structure 62,  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 68 is lattice matched to GaN channel layer 66 and  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  exhibits no piezoelectric polarization field. QW structure 62 exhibits high differential spontaneous polarization for the  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$  hetero-interface. Moreover, QW structure 62 does not have the negative effects related to the barrier layer relaxation.

In general, nitrides-based quantum layers exhibits piezoelectric field ( $P_{\text{piezo}}$ ) and spontaneous polarization ( $P_0$ ). Nitrides crystal structure has no inversion symmetry and consequently for strained III-nitride epitaxial layers grown in the (0001) orientation, a piezoelectric polarization will be present along the [0001] direction. The piezoelectric polarization field is given by  $P_{\text{piezo}} = (e_{31} - e_{33}C_{31}/C_{33}) \epsilon_1$ , where  $e_{31}$ ,  $e_{33}$  are piezoelectric constants,  $C_{31}$ ,  $C_{33}$  are elastic constants, and  $\epsilon_1 = \epsilon_{xx} + \epsilon_{yy}$  is in-plane strain. If  $a_0$  is the lattice constant of the relaxed epitaxial layer (i.e., under no strain) and  $a$  is the lattice constant after strain has been applied (i.e., the lattice constant of the layer to which the strained layer is lattice matched), then the strain  $\epsilon_1$  can be calculated as  $\epsilon_1 = 2(a - a_0)/a_0$ . Moreover, even if the strain is not present, nitride ionicity and structure uniaxial nature causes spontaneous polarization field  $P_0$ . The total polarization field is related to the polarization-induced charge density  $\rho_{\text{total}}$  according to  $-\rho_{\text{total}} = \nabla \cdot (P_{\text{piezo}} + P_0)$ . In other words, the hetero-interface junction exhibits polarization sheet charge density arising from the difference  $\Delta P_0$  in spontaneous polarization between the two materials and from the change in strain that defines the  $P_{\text{piezo}}$ . The difference in polarization fields produces charge densities that may act as donors or acceptors, respectively. If at the given hetero-interface the  $\rho_{\text{total}}$  is positive, then free electrons with the density of  $n_{\text{total}} = \rho_{\text{total}}/q$ , where  $q$  denotes for the electron charge, are accumulated at the hetero-interface to compensate the polarization induced charge. Similarly, a negative  $\rho_{\text{total}}$  can cause an accumulation of holes if the valence band edge crosses the Fermi level at the hetero-interface.

Table 1 shows values for relevant physical parameters for AlN, GaN and InN.

Spontaneous polarization field ( $P_0$ ) of ternary compounds is calculated by applying Vegard's law:  $P_0(\text{A}_x\text{B}_{1-x}\text{C}) = P_0(\text{BC}) + x(P_0(\text{AC}) - P_0(\text{BC}))$ . Vegard's law can be analogously applied for any other physical parameter listed in Tab.1. Polarization orientation is dependent on the polarity of the crystal, i.e., whether cation (Ga, Al, In)

or the anion (N) bonds face the surface. Cation polarity for all materials is mostly expected for properly grown device-quality layers. The physical properties of the HEMT QW structure are important for determining transistor performance.

	AlN	GaN	InN
$e_{33} (\text{Cm}^{-2})$	1.46	0.73	0.97
$e_{31} (\text{Cm}^{-2})$	-0.60	-0.49	-0.57
$e_{31} - (C_{31}/C_{33}) e_{33}$	-0.86	-0.68	-0.90
$a_0 (\text{\AA})$	3.112	3.189	3.548
$P_0 (\text{Cm}^{-2})$	-0.081	-0.029	-0.032

TABLE 1

The following description is based on a HEMT analytical model as described in IEEE Transactions on Electron Devices, vol. ED-30, pages 207-212, 1983 and is here modified for the polarization-induced charge to calculate the basic HEMT DC parameters. The two-dimensional gas carrier density  $n_s$  is given by

$$n_s = \varepsilon (V_G - V_T)/qd \quad (1)$$

where  $V_G$  is a gate voltage,  $V_T$  is a HEMT threshold voltage,  $\varepsilon$ ,  $d$  are barrier layer permittivity and thickness, respectively, and  $q$  is an electron charge. We incorporate the polarization-induced charge into the calculation of  $V_T$  wherein the barrier layer is considered to be un-doped:

$$V_T = \Phi_b - \Delta E_C - d\rho_{\text{total}}/\varepsilon \quad (2)$$

wherein  $\Phi_b$  is a Schottky contact barrier height. A drain-to-source saturation current  $I_{\text{sat}}$  can be calculated as

$$I_{\text{sat}} = (\beta V_s^2 (1 + 2\beta R_s V'_G + V'^2_G / V_s^2)^{1/2} - (1 + \beta R_s V'_G)) / (1 - \beta^2 R_s^2 V_s^2) \quad (3)$$

wherein  $R_s$  is a parasitic source resistance and

$$V'_G = V_G - V_T \quad (4)$$

$$V_s = v_s L / \mu \quad (5)$$

$$\beta = \varepsilon \mu W / dL \quad (6)$$

where  $v_s$  is an electron saturation velocity,  $L$  is a gate length  $\mu$  is a low field mobility of the QW electron gas and  $W$  is a gate width. Effects related to transistor self-heating are not considered in our model.

Referring again to Fig. 4A, QW structure 62 exhibits a high electron density of 2DEG due to high differential spontaneous polarization for the  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$  hetero-interface, as shown in the Table 2 below. Importantly, QW structure 62 does not have the negative effects related to the barrier layer relaxation. This QW structure enables high current and power performance of HEMT 60, as explained in connection with Fig. 6.

FIG. 4B illustrates a band gap diagram of another HEMT. Similarly as HEMT 60, shown in Fig. 4, HEMT 60A includes a substrate, a quantum well (QW) structure 62A and the electrodes. Quantum well structure 62A includes an AlN buffer layer, an un-doped GaN layer 66, and an un-doped InAlN layer 68A. A doped  $n^+$ -GaN layer is used to form ohmic contacts with the source and drain electrodes. HEMT 60A has the same cross-sectional diagram as HEMT 60, shown in Fig. 4. Furthermore, HEMT 60A is fabricated using the same processing steps as HEMT 60.

In quantum well structure 62A,  $\text{In}_{0.25}\text{Al}_{0.75}\text{N}$  barrier layer 68A is compressively strained to channel layer GaN 66. The compressively strained  $\text{In}_{0.25}\text{Al}_{0.75}\text{N}$  barrier layer 68A exhibit piezoelectric field acting against the electron accumulation in the QW, as shown in Fig. 4B. Consequently, the electron density  $n_{\text{total}}$  is reduced in comparison to HEMT 60, but still by 29 % higher than for a AlGaN/GaN QW structure, as calculated in Tab 2. The QW structure 62A enables high current and power performance of HEMT 60A, as explained in connection with Fig. 6A.

When designing the  $\text{In}_x\text{Al}_{1-x}\text{N}$  composition for the barrier layer at about  $x < 0.17$  the compressive strain changes to tensile strain. The corresponding piezoelectric field changes its orientation and thus increases the QW electron accumulation. On the other hand, the  $\text{In}_x\text{Al}_{1-x}\text{N}$  composition of about  $x > 0.25$  leads to further 2DEG density decrease and thus about  $x = 0.25$  is considered as a maximal reasonable value for HEMT 60.

FIG. 5 illustrates diagrammatically a III-nitride HEMT 80 according to another embodiment. HEMT 80 includes a substrate 81, a quantum well (QW) structure 82, and electrodes 94 and 96. Preferably, quantum well structure 82 includes an AlN buffer layer 84, an un-doped GaN layer 86, an un-doped  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88, and an  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 90. HEMT 80 also includes a doped  $n^+$ -GaN layer 92 used to form ohmic contacts with source and drain electrodes 96.

In HEMT 80, reference numeral 81 denotes for a (0001) 6H-SiC substrate. AlN buffer layer 84 has a thickness in the range of about 5  $\mu\text{m}$  to about 40  $\mu\text{m}$ , and preferably about 20  $\mu\text{m}$ , and un-doped GaN layer 86 has a thickness of about 2  $\mu\text{m}$  and a carrier concentration less than about  $1 \times 10^{16} \text{ cm}^{-3}$ . The un-doped  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88 has a thickness in the range from few nm up to a critical thickness when relaxation appears, and preferably about 10 nm. The  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 90 has a thickness in the range from about 5 nm to about 30 nm, and preferably about 15 nm. Highly doped  $n^+$  GaN cap layer (having a thickness in the range from about 5 nm to about 30 nm, and preferably about 15 nm and a carrier concentration in the range of  $10^{18} \text{ cm}^{-3}$  to  $10^{19} \text{ cm}^{-3}$ , and preferably more than about  $5 \times 10^{18} \text{ cm}^{-3}$ ) provides ohmic contacts to Ti/Al/Ni/Au source and drain electrodes 96. A gate electrode 94 is made of a Pt/Au film. HEMT 80 is fabricated using a similar process as described in connection with HEMT 60.

FIG. 5A illustrates a band gap diagram of the  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  QW structure 82.  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88 is compressively strained between GaN layer 86 and  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  barrier layer 90. Piezoelectric polarization field appears across channel 88. As shown in Table 2, the strain in  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88 is beneficial for further increase of the free electron density  $n_{\text{total}}$ . Differential spontaneous polarization at the GaN/ $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  hetero-interface not mentioned in the Table 2 has the value of  $3 \times 10^{-8} \text{ Ccm}^{-2}$  and can be neglected.

Table 2 includes physical parameters for the various heterostructures described herein. Polarization-induced QW 2DEG densities  $n_{\text{total}} = p_{\text{total}}/q$  were calculated using the above theory. QW structures shown in Figs. 4, 4A, 4B, 5, 5A, 5B and 5C exhibit high values of  $n_{\text{total}}$  with highest values for QW structure made of compressively strained  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88 and tensile strained  $\text{In}_{0.15}\text{Al}_{0.85}\text{N}$  barrier layers 90A (shown and described in connection with Fig. 5B).

FIG. 5B illustrates a band gap diagram of another HEMT 80A related to HEMT 80. HEMT 80A includes a substrate, a quantum well (QW) structure 82A, and the source, drain and gate electrodes. Quantum well structure 82A includes an AlN buffer layer, an un-doped GaN layer 86, an un-doped  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88, and an  $\text{In}_{0.15}\text{Al}_{0.85}\text{N}$  barrier layer 90A. HEMT 80A also includes a doped  $n^+$ -GaN layer used to form ohmic contacts with the source and drain electrodes, similarly as shown in Fig. 5.

Heterostructure	$\Delta P_0$ (Ccm <sup>-2</sup> )	$P_{\text{piezo}}$ (Ccm <sup>-2</sup> )	$n_{\text{total}}$ (cm <sup>-2</sup> )	$\Delta E_C$ (eV)
<b>Al<sub>0.2</sub>Ga<sub>0.8</sub>N/ GaN</b>	$-1.04 \times 10^{-6}$	$-6.9 \times 10^{-7}$	$1.08 \times 10^{13}$	0.3(0.75 $\Delta E_g$ )
<b>In<sub>0.17</sub>Al<sub>0.83</sub>N/ GaN</b>	$-4.37 \times 10^{-6}$	0	$2.73 \times 10^{13}$	0.68
<b>In<sub>0.25</sub>Al<sub>0.75</sub>N/ GaN</b>	$-3.97 \times 10^{-6}$	$1.74 \times 10^{-6}$	$1.39 \times 10^{13}$	0.65
<b>In<sub>0.17</sub>Al<sub>0.83</sub>N/ In<sub>0.10</sub>Ga<sub>0.90</sub>N</b>	$-4.34 \times 10^{-6}$	$1.6 \times 10^{-6}$	$3.71 \times 10^{13}$	>0.68
<b>In<sub>0.15</sub>Al<sub>0.85</sub>N/ In<sub>0.10</sub>Ga<sub>0.90</sub>N</b>	$-4.44 \times 10^{-6}$	$1.6 \times 10^{-6}$ (InGaN)	$4.16 \times 10^{13}$	>0.68
		$-6.2 \times 10^{-7}$ (InAlN)		
<b>In<sub>0.30</sub>Al<sub>0.70</sub>N/ In<sub>0.10</sub>Ga<sub>0.90</sub>N</b>	$-3.72 \times 10^{-6}$	$1.6 \times 10^{-6}$ (InGaN)	$1.5 \times 10^{13}$	>0.6
		$2.9 \times 10^{-6}$ (InAlN)		

TABLE 2

Referring to Fig 5B, in In<sub>0.15</sub>Al<sub>0.85</sub>N/In<sub>0.10</sub>Ga<sub>0.90</sub>N/GaN QW structure 82A In<sub>0.10</sub>Ga<sub>0.90</sub>N channel layer 88 is compressively strained to GaN layer 86. There is piezoelectric polarization field across the channel layer 88. The In<sub>0.15</sub>Al<sub>0.85</sub>N barrier layer 90A exhibit an additional tensile strain. Orientation of the barrier layer piezoelectric field is opposite to the In<sub>0.10</sub>Ga<sub>0.90</sub>N channel piezoelectric field, but points to the QW structure and causes further electron accumulation (Table 2). This QW structure enables high current and power performance of HEMT 80A, as explained in connection with Fig. 6A.

FIG. 5C illustrates a band gap diagram of another HEMT 80B related to HEMT 80. HEMT 80B includes a substrate, a quantum well (QW) structure 82B, and the source, drain and gate electrodes. Quantum well structure 82B includes an AlN buffer layer, an un-doped GaN layer 86, an un-doped In<sub>0.10</sub>Ga<sub>0.90</sub>N channel layer 88, and an In<sub>0.3</sub>Al<sub>0.7</sub>N barrier layer 90B. HEMT 80B also includes a doped n<sup>+</sup>-GaN layer used to form ohmic contacts with the source and drain electrodes, similarly as shown in Fig. 5.

Quantum well structure 82B has  $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  channel layer 88 compressively strained to GaN layer 86. The piezoelectric polarization field appear across channel layer 88, as shown in Fig 5C. The  $\text{In}_{0.30}\text{Al}_{0.70}\text{N}$  barrier layer 90B also exhibit additional compressive strain. The orientation of the barrier layer piezoelectric field is opposite the orientation in layer 90A (Fig. 5B) and causes a decrease in the electron density of 2DEG (as seen from Table 2). However, the total free electron density ( $n_{\text{total}}$ ) is still by about 40 % higher than for AlGaN/GaN QW shown in Fig. 3. The corresponding increase in drain current is calculated in FIG. 6A. Further increase of In molar fraction  $x$  beyond 0.30 may cause layer relaxation and thus this value can be considered as a maximal reasonable value for HEMT 80B.

Figs. 6 and 6 A displays calculated transfer and transconductance characteristics of the above-described HEMTs. The drain current (y-axis) was calculated for  $I_{\text{sat}}$  using Eq. 3 together with Eqs. 1, 2, 4, 5 and 6 as a function of the HEMT gate voltage  $V_G$  (x-axis). The values  $\Phi_b = 1 \text{ eV}$ ,  $R_s = 1.5 \Omega\text{mm}$ ,  $\mu = 1000 \text{ cm}^2/\text{Vs}$ ,  $v_s = 1.2 \times 10^5 \text{ m/s}$ ,  $d=15 \text{ nm}$  were used in the calculations. The transconductance plotted on y-axis was calculated as the derivative of the drain current by the gate voltage ( $dI_{\text{sat}}/dV_G$ ) and is plotted as a function of gate voltage.

Specifically, Fig. 6 displays calculated transfer and transconductance characteristics for a 200 nm gate-length of HEMTs 60 and 80 compared to prior art  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$  HEMT 40. High transconductance values make the HEMTs suitable for high speed applications and a high drain current density makes them suitable for high power performance.

FIG. 6A displays calculated transfer and transconductance characteristics for 200 nm gate-length of HEMTs 60A, 80A and 80B compared to prior art  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$  HEMT 40. The  $\text{In}_{0.15}\text{Al}_{0.85}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  HEMT (HEMT 80A) exhibit a very high drain current density of about 4.2 A/mm, which represents a 255 % increase compared to the AlGaN/GaN HEMT. The characteristics of  $\text{In}_{0.30}\text{Al}_{0.70}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  (HEMT 80B) and  $\text{In}_{0.25}\text{Al}_{0.75}\text{N}/\text{GaN}$  (HEMT 60A) show some improved performance when compared with the AlGaN/GaN HEMT.

Theoretical characteristics in FIG. 6 show the maximum transconductance over 300 mS/mm and an open channel drain current of about 1.2 A/mm for the conventional  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$  HEMT. These results coincide well with already

published best values for 0.15-0.2  $\mu\text{m}$  gate length  $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$  HEMTs. For  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{GaN}$  HEMT 60, FIG. 6 shows only slight increase in transconductances (by about 7 %) but an about 125 % increase of accessible drain currents and 2.7 A/mm drain current should be accessible. Furthermore, in comparison to conventional  $\text{AlGaIn}/\text{GaN}$  HEMT,  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$  HEMT indicates 210 % current increase and 3.7 A/mm drain current density.

Fig. 7 depicts for various III-nitrides the dependence of energy gap ( $\Delta E_g$ ) on lattice constant ( $a_0$ ) at 300 K. This dependence is useful for designing a QW structure of desired properties. For the plotted III-nitrides, the lattice constant  $a_0$  decreases as a function of the Al molar fraction in Al nitride. Thus, to increase the carrier density ( $n_{\text{total}}$ ) for a  $\text{AlGaIn}/\text{GaN}$  QW structure, it is suitable to increase the strain in the barrier layer by increasing the amount of Al in the  $\text{AlGaIn}$ . However, a possible relaxation of the barrier layer, which diminishes piezoelectric polarization ( $P_{\text{piezo}}$ ), may present a problem. Moreover, the crystallographic quality of  $\text{AlGaIn}$  is decreased for higher Al molar fraction, as structural defects may appear during the growth. This can lead to poor Schottky (gate) contacts parameters. On the other hand higher piezoelectric field can be obtained for  $\text{InAlN}/(\text{In})\text{GaIn}$  QW structures even with smaller strain  $\epsilon_1$  if compared to conventional  $\text{AlGaIn}/\text{GaIn}$ . This can be seen by comparing ( $e_{31} - e_{33}C_{31}/C_{33}$ ) of  $\text{In}_x\text{Al}_{1-x}\text{N}$  and  $\text{Al}_z\text{Ga}_{1-z}\text{N}$  for a given  $\epsilon_1$ . The  $\text{In}_x\text{Al}_{1-x}\text{N}$  barrier layer is superior to  $\text{Al}_z\text{Ga}_{1-z}\text{N}$  basically because of higher Al molar fraction in  $\text{In}_x\text{Al}_{1-x}\text{N}$  as for  $\text{Al}_z\text{Ga}_{1-z}\text{N}$  with the same strain. High Al molar fraction in  $\text{In}_x\text{Al}_{1-x}\text{N}$  is also responsible for high differential spontaneous polarization field in the  $\text{InAlN}/(\text{In})\text{GaIn}$  QW structure. Moreover, the  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  layer can be grown lattice matched to GaN while for the  $\text{AlGaIn}$  similar Al molar fraction may lead to critical lattice strain and layer relaxation can occur.

The above described HEMT 60, 60A, 80, 80A and 80B exhibit increased 2DEG density and HEMT drain current capability with a decrease in In molar fraction ( $x$ ) in the barrier layer  $\text{In}_x\text{Al}_{1-x}\text{N}$ . Electron density values as high as  $n_{\text{total}} = 4.16 \times 10^{13} \text{ cm}^{-2}$ , and drain current  $I_{\text{sat}} = 4.2 \text{ A/mm}$  were calculated for tensile strained  $\text{In}_x\text{Al}_{1-x}\text{N}$ ,  $x=0.15$ . On the other hand, for the values of  $x>0.17$ , the strain in the barrier layer becomes compressive and for about  $x \approx 0.25-0.30$  the superiority of the novel

InAlN/(In)GaN type HEMTs, in comparison to prior art AlGaIn/GaN HEMT 40 disappears.

Advantageously, the wide band gap of InAlN enables high breakdown voltages. Furthermore, deeper InAlN/(In)GaN QW structures improves the QW carrier confinement. Finally we conclude that  $\text{In}_x\text{Al}_{1-x}\text{N}$  containing barrier layer provides III-nitrides HEMTs with a new quality exhibiting a record drain current/power capabilities. In HEMTs 60, 60A, 80, 80A and 80B, the high transconductance values confirm that these devices are uniquely suitable for high-frequency applications.

According to a preferred embodiment, HEMT (or HFET) devices are designed to have a maximal accumulated 2DEG in the HEMT channel. This accumulation is affected by spontaneous polarization or piezoelectric polarization or both. Regarding the charge induced by spontaneous polarization, the HEMTs (or HFETs) can be designed to have preferably the maximal difference in polarization fields keeping in mind the polarity of the layers. Based on Table 1, according to one preferred embodiment, the maximal value of  $\Delta P_0$  can be obtained for AlN/GaN or AlN/InN-based junctions. Therefore, for cation-polarity layers, the HEMTs can include a InAlN or AlGaIn barrier layer on top of the (In)GaIn channel, while keeping the highest possible Al molar fraction in the barrier. While a  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}$  layer can be grown lattice matched to a GaIn layer, a AlGaIn layer with a similar Al molar fraction may lead to critical lattice strain and layer relaxation. Therefore, the preferred embodiments includes a InAlN/(In)GaIn QW structure.

Regarding the charge induced by the piezoelectric polarization, the HEMTs (or HFETs) can be designed keeping in mind the layers cation-polarity. To get the highest 2DEG in the QW structure, there are the following factors regarding the barrier layer on top of the channel. The QW structure should include either a compressively strained channel layer or a tensile strained barrier layer or both. Preferably, a wide bandgap barrier layer includes  $\text{In}_x\text{Al}_{1-x}\text{N}$  ( $x \leq 0.17$ ) or  $\text{Al}_z\text{Ga}_{1-z}\text{N}$  ( $0 \leq z \leq 1$ ), while the channel includes  $\text{In}_y\text{Ga}_{1-y}\text{N}$  ( $0 \leq y \leq 1$ ). The piezoelectric polarization is calculated as follows:  $P_{\text{piezo}} = (e_{31} - e_{33}C_{31}/C_{33})\epsilon_1$  where  $e_{31}$ ,  $e_{33}$  are piezoelectric constants,  $C_{31}$ ,  $C_{33}$  are elastic constants and  $\epsilon_1 = \epsilon_{xx} + \epsilon_{yy}$  is in-plane strain. Therefore, for a maximal acceptable strain (i.e.,  $\epsilon_1$  can be further considered as a constant), a very important factor is represented by the value of  $(e_{31} - e_{33}C_{31}/C_{33})$ , which should be also maximal. When comparing the value of  $(e_{31} -$



$e_{33}C_{31}/C_{33}$ ). for  $\text{In}_x\text{Al}_{1-x}\text{N}$  and  $\text{Al}_z\text{Ga}_{1-z}\text{N}$ , for given  $\epsilon_1$  the  $\text{In}_x\text{Al}_{1-x}\text{N}$  barrier layer is again preferred over  $\text{Al}_z\text{Ga}_{1-z}\text{N}$  basically because of higher Al molar fraction in  $\text{In}_x\text{Al}_{1-x}\text{N}$  as for  $\text{Al}_z\text{Ga}_{1-z}\text{N}$  with the same strain. These rules can be applied to other types of materials when designing a QW structure.

In Figs. 8 and 9 we show calculated QW free electron density  $n_{\text{total}}$ , HEMT open channel drain current and threshold voltage as well as strain as a function of In molar fraction in  $\text{In}_x\text{Al}_{1-x}\text{N}/\text{GaN}$  or  $\text{In}_{0.17}\text{Al}_{0.83}\text{N}/\text{In}_y\text{Ga}_{1-y}\text{N}$  QW structures, respectively. As indicated by the right y-axes scales, critical (maximal) acceptable strain for 15 nm thick InAlN (Fig.8) and 5-10 nm thick InGaN (Fig.9) was estimated to be 0.0125 and 0.02 respectively.

According to another embodiment, the above described HEMT 60, 60A, 80, 80A and 80B may also be created by engineering the bandgap profile of the barrier layer, i.e., step-wise changing or continuously decreasing the Al molar fraction in the InAlN barrier layer. These types of HEMTs exhibit a significantly decreased source resistance. U.S. Patent 6,064,082 to Kawai, et al. (incorporated by reference) discloses a variation in the bandgap profile by changing the barrier layer. Kawai continuously decreased the Al molar fraction in the AlGaN barrier layer in direction to the contact layer. The transistor of Kawai however does not involve the polarization phenomena used in the above-described HEMTs, nor suggests using of InAlN based barrier layer..

According to yet another embodiment, the above-described HEMTs 60, 60A, 80, 80A and 80B may also be created by forming a multi-layered channel structure. A multi-layered channel structure was used in a nitride-type III-V group HEMT described in U.S. Patent No.6,177,685. This HEMT uses a channel layer with a multi-layered structure containing InN, which according to the 6,177,685 patent, provides an increased 2DEG mobility in the HEMT channel. The above-described HEMTs 60, 60A, 80, 80A and 80B may also use a InN/GaN multi-layered structure in the channel in addition to the InAlN in place of the barrier layer. However, U.S. Patent No. 6,177,685 does not disclose or even suggest using InAlN in place of the barrier layer or specifically envisions the use of the polarization phenomena.

According to yet another embodiment, the above-described HEMTs 60, 60A, 80, 80A and 80B may also be fabricated by using a doped layer in the QW structure.

In this case, both the polarization phenomena and impurity doping affects the 2DEG layer formed in the HEMT channel.

In general, possible applications include transmissions from Direct Broadcast Satellites (DBS) operating at about 12 GHz (but generally any communication system operating at frequencies in the range of 1 GHz to 400 GHz). A DBS outdoor receiver unit includes RF amplifier and filter, mixer, intermediate frequency amplifier and local oscillator. Other applications include cellular radio and radar applications such as radars for vehicle collision avoidance. Monolithic microwave or millimeter wave integrated circuits (MMICs) may also find application in instrumentation, for example, in frequency synthesizers, network analyzers, spectrum analyzers and sampling oscilloscopes.

Furthermore, the above described HEMTs may also be used in radars with electronically-steerable beams, known as phase-arrays, MMIC amplifiers, mixers, MMIC RF drivers, and MMIC phase shifters, or any other devices that require a high-frequency operation (1 GHz to 400 GHz), high power, low noise, or any combination thereof.

In short, the above-described HEMTs 60, 60A, 80, 80A and 80B are suitable for high frequency and high power applications such as needed for portable phones, satellite broadcasting, satellite communication systems, land-based communication systems (see IEEE Spectrum, Vol. 39 (2002), No.5, pp.28-33) and other systems that use high-frequency waves such as microwaves or millimeter waves. In these systems, high-power amplifiers (preferably having low noise) are used for amplification or signal transmission.

Specifically, the above-described HEMTs 60, 60A, 80, 80A and 80B are suitable for use in portable telephones such as the portable telephones disclosed in U.S Patent 6,172,567, which is incorporated by reference. The above-described HEMTs 60, 60A, 80, 80A and 80B are also suitable for use in communication systems, such as the communication systems disclosed in U.S Patent 6,263,193 or U.S. Patent 6,259,337, both of which are incorporated by reference. The above-described HEMTs 60, 60A, 80, 80A and 80B are suitable for use in direct broadcast satellite systems such as the direct broadcast satellite systems disclosed in U.S

Patent 5,649,312 or U.S. Patent 5,940,750, both of which are incorporated by reference.

The above-described HEMTs 60, 60A, 80, 80A and 80B are suitable for construction of low noise amplifiers (LNAs). These amplifiers are optimized for minimum noise and are used in receiver front ends, for example, in wireless telecommunications, radar sensors, and in IF amplifiers for radioastronomy receivers. HEMTs 60, 60A, 80, 80A and 80B may be used for construction of low noise amplifiers such as the noise amplifiers disclosed in U.S. Patent 5,933,057 or U.S. Patent 5,815,113, both of which are incorporated by reference. Furthermore, HEMTs 60, 60A, 80, 80A and 80B may be used for construction of intermediate frequency amplifiers such as the intermediate frequency amplifiers disclosed in U.S. Patent 5,528,769 or U.S. Patent 5,794,133, both of which are incorporated by reference. Furthermore, HEMTs 60, 60A, 80, 80A and 80B are suitable for construction of power amplifiers such as the power amplifiers disclosed in U.S. Patent 6,259,337 or U.S. Patent 6,259,335, both of which are incorporated by reference.

Furthermore, the above-described HEMTs 60, 60A, 80, 80A and 80B are suitable for use in radar systems such as the radar systems disclosed in U.S. Patent 6,137,434 or in U.S. Patent 6,094,158, both of which are incorporated by reference. Other likely applications of the above-described HEMTs 60, 60A, 80, 80A and 80B include high performance radar units and LMDS (Local Multipoint Distribution Service) "wireless fiber" broadband links being developed for operation at 28GHz and 31GHz, which is incorporated by reference for all purposes.

Furthermore, the above-described HEMTs 60, 60A, 80, 80A and 80B are suitable for construction of sensor systems such as the sensor systems disclosed in U.S. Patent 6,104,075 or U.S. Patent 5,905,380, both of which are incorporated by reference.

The above-described HEMTs 60, 60A, 80, 80A and 80B can be fabricated on and incorporated in monolithic microwave or millimeter wave integrated circuits (MMICs). These circuits include voltage controlled oscillators at selected discrete frequencies up to 350 GHz, low-noise amplifiers at selected frequencies in the range of 1 GHz and 350 GHz or frequency ranges (generally selected frequencies from 1

GHz up to 400 GHz), phase shifters, and resistive and active mixers at frequencies in the range of 1 GHz up to 250 GHz (and even 350 GHz or 400 GHz).

The above-described HEMTs 60, 60A, 80, 80A and 80B can be fabricated on and incorporated in GaN-based MMIC attenuators (see E.Alekseev, Broadband AlGaIn/GaN HEMT MMIC Attenuators with High Dynamic Range, 30<sup>th</sup> European Microwave Conference, Paris, October 2000) using HEMTs broadband and high-dynamic range characteristics and very high power handling, which is incorporated by reference for all purposes.

The above-described HEMTs 60, 60A, 80, 80A and 80B may be used in various hybrid circuits and systems. For example, instead of building a complete transceiver MMIC system from the monolithic components described above, the HEMTs are used in hybrid systems (MMIC systems would require circuits that are too large and expensive to be created on a single substrate). One negative side effect of using transmission line matching networks is that they use a lot of chip area for purely passive elements. Microstrip circuits for mm-wave applications using discrete HEMTs or individual monolithic circuits can reduce the system cost massively. These may be mounted next to other discrete devices upside-down onto a dielectric microstrip circuit using various packaging techniques such as flip-chip bonding using gold-bumps.

The present invention was described with reference to the above aspects and embodiments, but the invention is by no means limited to the particular embodiments described herein and/or shown in the drawings, alone or in combination with the above-cited publications (all of which are incorporated by reference). The present invention also comprises any modifications or equivalents within the scope of the following claims.